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Permalink
https://escholarship.org/uc/item/3mg8g66b

Journal
American Journal of Enology and Viticulture, 72(1)

ISSN
0002-9254

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Publication Date
2021

DOI
10.5344/ajev.2020.20012

Peer reviewed

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2020.20012

Research Article

Compost Application to Degraded Vineyard Soils: Impact on Soil Chemistry, Fertility, and Vine Performance

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Acknowledgments: The authors thank Gallo Family Vineyards and Snows Lake Vineyard team for analysis, insights, and labor. Special thanks is extended to Brodie McCarthy, viticulturist, Gallo Family Vineyards.

Manuscript submitted Feb 16, 2020, revised June 29, 2020, Sept 5, 2020, accepted Sept 15, 2020

Abstract: A two-year experiment investigated the effects of compost application rate on soil chemical properties, vine nutrient status, vine performance, and grape juice characteristics in a degraded vineyard soil in northern California. The intent of the research was to identify vineyard management strategies to improve soil fertility and to identify optimal compost application rates. We applied composted steer manure at three rates (11.2, 22.4, 33.6 t/ha) in a randomized complete block design before the 2012 growing season. Pruning and berry weight increased over the control at the highest application rate in both years, while vine yield significantly increased over the control in year two. Polynomial orthogonal contrasts suggest that pruning weight, vine yield and berry weight increased linearly with increasing compost application rate in 2012, and that vine yield and berry weight increased linearly and quadratically with compost application rate in 2013. Measured soil properties increased from compost application, including N, C, pH, exchangeable K, Mg and Ca and available P (Olsen-P), while phosphorus fixation

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decreased. Vine petiole nutrients (N, P, K) significantly increased from compost application in both years. Juice characteristics (pH, total soluble solids, and titratable acidity) were unaffected by compost application. Similarly, vine balance was unaffected by compost application. All vine metrics improved at the highest application rate, and soil chemical properties increased with the two highest application rates. Therefore, significant benefits to soil fertility and vine performance can be achieved for at least two years in degraded vineyard soils following a single dose of compost at a higher application rates (22.4 and 33.6 t/ha) without compromising juice characteristics or vine balance.

Key words: grape yield, grapevine nutrition, soil fertility, vine health, viticulture practices

Introduction

Soil degradation and decline of soil quality in vineyard soils are widespread (Ramos and Martínez-Casasnovas 2006a). Winegrape production is often conducted on low organic matter soils in Mediterranean-type climates, subject to intense rainfall events and significant erosion (Battany and Grismer 2000, Martínez-Casasnovas and Ramos 2006, Ramos and Martínez-Casasnovas 2006a). Further, vineyard expansion into steeply sloping sites, clearing of native vegetation, extensive earth moving and cultural practices, such as cultivation and bare floor management, lead to increased erosion and declines in soil quality that manifest in decreased soil organic carbon (SOC) and plant nutrients (Battany and Grismer 2000, Blavet et al. 2009). For example, increased land alteration in Spanish vineyards, including deep ploughing and land leveling, led to truncation of soil profiles, low SOC (0.16-0.53%) and soil nitrogen (N) losses reaching 14.9 kg N/ha/yr (Ramos and Martínez-Casasnovas 2006b, Martínez-Casasnovas and Ramos 2009). Loss of surface soils, either through vineyard development or accelerated erosion, results in a subsequent decline in soil microbial activity and nutrient cycling capacity (Blavet et al. 2009). Declines in vine productivity due to degradation of vineyard soils can be significant, leading to

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yield reductions as high as 50% (Ramos and Martínez-Casasnovas 2006a). Given these declines in crop and soil quality in vineyard soils, practices to restore vineyard soil quality merit further investigation.

One widely adopted method to improve soil quality in vineyards is through the application of composts or other organic inputs (Morlat and Chaussod 2008, Gaiotti et al. 2017). Calleja-Cervantes et al. (2015) reported increased SOC, soil nutrients and bacterial biodiversity following application of composted sheep manure to a calcareous vineyard soil for 12 years. Similarly, Bustamante et al. (2011) found increases of SOC, soil nutrients and soil respiration following application of several different types of composts to a calcareous vineyard soil. In a previous study of composted steer manure addition to a highly weathered vineyard soil derived from obsidian in northern California, we found increased soil pH, microbial biomass carbon, dissolved organic carbon and phosphorus (P) availability following compost addition (Wilson et al. 2016). Rubio et al. (2013) investigated application of different types of composts, including a mixed cattle manure and grape waste compost, to a calcareous soil in Spain and found an initial decrease in soil pH, along with increases in nitrate, oxidizable carbon and microbial biomass carbon, as well as increased vine yield. Therefore, compost application to vineyard soils can improve soil quality, with inputs of SOC leading to improved physical and chemical characteristics, soil nutrients and biological activity.

While improvements to vineyard soil quality from compost application are clear, the results from compost application on grapevine performance are mixed. For example, in some investigations, application of composted manures and mulches improved soil physical properties and increased per vine yield (Pinamonti 1998, Gaiotti et al. 2017, Ramos 2017). Conversely, Morlat and Chaussod (2008) applied high rates (20 t/ha) of compost to a calcareous soil in France, and observed increased soil quality metrics, but a reduction in vine performance. Other studies found no significant effects on vine performance or soil quality following the application of composts (Schmidt et al. 2014). Thus, while

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compost application has clear benefits to vineyard soil quality (e.g., physical, chemical, and biological properties), the effects on vine performance remain contradictory, highlighting the need for further study.

Given the paucity of relevant research and the focus on soil quality prescriptions in vineyard soils, as well as the contradictory results of studies investigating the effects of compost application on vine performance, we undertook a two-year study examining compost application rates on a degraded (e.g., truncated by erosion) volcanic soil in the North Coast winegrape growing region of California. Our objective was to ascertain the effect of three compost application rates (11.2, 22.4, 33.6 t/ha) on vine performance, juice quality, vine nutrient status and soil properties for two growing seasons following a single compost application. Results from this study inform beneficial management practices to restore underperforming vineyards and improve soil fertility, providing information on optimum compost application rates, vine performance and nutrition, as well as consequences to soil and grape juice quality. Further, compost application has been promoted as a potential carbon sequestration practice, necessitating further study (Longbottom and Petrie 2015).

Methods and Materials

Site and vineyard description. The study site in the North Coast region of California (Lake County, CA) is within the Red Hills American Viticultural Area (AVA), a delimitated area of winegrape production with distinguishing features that include volcanic soils. Climate is Mediterranean with an average annual precipitation of 800 mm occurring primarily as rainfall from November to March, and a mean annual air temperature of 14°C. The vineyard consists of Cabernet Sauvignon on 3309-C rootstock, planted in 2001 at a density of 2,692 vines per hectare with shoots trained on a vertical shoot positioning trellis system. Cultural practices were according to grower standard practice and were the same for all experimental treatments. Shoots were thinned on all vines pre bloom, but clusters were not thinned and vines were not hedged. During the two-year study, bloom occurred on 6/5/2012 and 5/19/2013. Vines

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were drip irrigated based on midday leaf water potential (pressure bomb measurements) with a target range from -1.2 to -1.3 MPa between bloom and harvest. Vines received fertigation using grower standard practices, with applications of 14.6 kg N/ha/yr and 17.9 kg P/ha/yr.

Soils in the vineyard are clay rich (20 – 40% clay) and highly weathered Alfisols and Ultisols, formed on an early Holocene andesitic volcanic flow (Wilson et al. 2017). Soil map units consisted of the Aiken (Fine, parasesquic, mesic Xeric Haplohumult) and Collayomi (Loamy-skeletal, mixed, active, mesic Ultic Haploxeralfs) soil series (Smith and Broderson 1989). Mineralogical and soil physical-chemical analyses were conducted on a nearby pedon, and published as part of a pedologic investigation (Wilson et al. 2017). Topography consisted of gently rolling hills, and the historical land-use was native oak woodland. A soil morphological investigation comparing adjacent wildland and cultivated soil profiles indicated considerable soil erosion prior to vineyard establishment resulting in truncation of the A horizon. Soil C concentrations in surface soil at the site (<1% C) were much lower than those found in surrounding native soils (2.9% C) (Wilson et al. 2017).

Experimental design and application rates. Compost was applied in January 2012 and the impact of compost addition was followed through the 2012 and 2013 growing seasons. The experimental design included four treatments (three compost rates [11.2, 22.4, 33.6 t/ha] and a control), in a randomized complete block design with 4 blocks, resulting in 16 experimental plots. Each experimental plot had 36 vines in three parallel rows, with only the central 10 vines of each treatment sampled to limit edge effects. We applied the compost as a single application in bands that were lightly incorporated (0 – 10 cm) into the soil directly under the vine row. Compost application was on a per hectare basis, with application banded and incorporated in the vine row by hand (Table 1 & 2). Compost consisted of composted steer manure with a C:N ratio of 12.5.

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Vine, fruit and juice sampling and analysis. Petioles were collected opposite inflorescences from the 10 central test vines in each experimental plot at bloom in 2012 and 2013, combined by replicate treatment, and sent to a commercial lab for standard nutrient analysis (Dellavalle Lab, Fresno, CA). At harvest, fruit was hand-harvested from the 10 central test vines in each experimental plot and weighed in the field, with weight reported on a kg per vine fresh weight basis. Two clusters from each vine were randomly sub-sampled after weighing and a total of 100-120 berries randomly selected and weighed as average berry weight in grams fresh weight. The remaining berries were crushed and analyzed for total soluble solids concentration (TSS) by hand refractometer, pH potentiometrically with a laboratory pH meter, and titratable acidity (TA) by titration to a pH 8.2 endpoint with 0.1 M NaOH. Following the 2012 and 2013 seasons (January of 2013 and 2014), pruning weight was collected from each test vine and reported on a kg per vine fresh weight basis. The Ravaz index, a measure of vine balance, was calculated as the ratio of yield to pruning weight (Ravaz 1912). Additionally, during harvest of the 2013 vintage, cluster numbers were counted, and cluster weight calculated as yield per vine divided by clusters per vine.

Soil sampling and analysis. Soils were sampled in the fall (early November) after harvest in both years to a depth of 15 cm directly in the center vine row of each experimental plot, thereby limiting edge effects, with 3 homogenized sub-samples per replicate (n=4). Soil samples were taken outside the drip zone. Soil samples were air-dried, gently crushed and sieved to pass through a 2-mm screen. Total C and N were measured on ground samples (<125 μm) with an ECS 4010 CHNSO Analyzer (Costech Analytical Technologies, CA, USA). A single point 75 mg PO_4-P kg^{-1} sorption index was used to characterize P-sorption potential (Sims 2009), expressed as mg-P sorbed per kg soil. Soil pH was determined after a 30-min equilibration using a 1:1 soil:water ratio. Cation exchange capacity (CEC) and extractable cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) were measured with 1 M NH_4OAc (pH 7.0) extraction (Burt 2004). Available phosphorus was determined via bicarbonate extraction (Olsen 1954).

Statistical analysis. All statistical analyses were performed in R using the *agricolae* package (de Mendiburu, 2020). For each year, compost treatment effects on soil, vine and juice attributes were tested independently using analysis of variance (ANOVA), with the significance level set at $p<0.05$. If treatment effects were significant, mean separation followed via Tukey's HSD ($p<0.05$). Both petiole N and P in 2013 were log transformed to satisfy the assumption of homogeneity of variance for ANOVA. Given equally spaced quantitative treatments (0, 11.2, 22.4 and 33.6 t/ha), we investigated polynomial (linear, quadratic and cubic) orthogonal contrasts to quantify the compost rate response in per vine yield, pruning weight and berry weight.

Results

Vine performance. While vine yield was ~0.8 kg/vine higher in 2012 following compost addition, a more than 50% increase, this increase was not significant. While vine yield showed a trend towards higher yield with higher application rates in 2012, only the 33.6 t/ha rate was significantly higher than the 11.2 t/ha rate (Figure 1A). Orthogonal polynomial contrasts suggest that vine yield had a significant linear increase with increased compost application rate in 2012 (Supplemental Table 1; $p<0.05$). Compared to yield, pruning weight was more responsive to compost application in 2012 (first year after application; $p<0.001$), with the highest application rate significantly different from all other treatments (Figure 1C). Berry weight showed a significant compost effect ($p<0.01$), with both the 22.4 and 33.6 t/ha treatments having significantly heavier berries than the control and 11.2 t/ha treatment (Figure 1E).

In 2013, compost application rate had a significant effect on yield ($p<0.01$). Pruning weight ($p<0.01$) and berry weight ($p<0.001$) were also significantly affected by compost application rate in the 2013 vintage. Vine yield was significantly higher in the 33.6 t/ha rate than 0 and 11.2 t/ha rates in 2013 (Figure 1B), while berry weight was significantly higher for the 22.4 and 33.6 t/ha rates compared to the

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2020.20012

control or the 11.2 t/ha rate (Figure 1F). Orthogonal polynomial contrasts suggest that yield had a linear ($p<0.001$) and quadratic ($p<0.05$) rate response with increased compost application rate (Supplemental Table 1). Pruning weight was significantly higher in the 33.6 t/ha rate compared to all other compost rates and control (Figure 1D).

Cluster number was not significantly affected by compost application ($p>0.05$), while cluster weight was affected ($p<0.001$). Clusters were heavier in the 33.6 t/ha treatment than all other treatments and control, while the 22.4 t/ha rate was heavier than the 11.2 t/ha rate, but not the control (data not shown). TSS, pH and TA were not significantly affected by compost application rate in either year ($p>0.05$). Similarly, vine balance, as measured by the Ravaz index, was not significantly affected by compost application in either vintage ($p>0.05$) (Table 3). Measured juice chemistry (pH, TA, TSS) and vine balance were not compromised by the higher yield induced by compost application (Table 3).

Vine nutrition. In 2012, petiole N ($p<0.01$), P ($p<0.001$) and K ($p<0.01$) all increased significantly from compost application (Table 4), especially in the 22.4 and 33.6 t/ha treatments; the 11.2 t/ha treatment was not different from the control. Increases in vine nutrient status were maintained in 2013 from the single application in the previous year, with petiole N ($p<0.05$), P ($p<0.01$) and K ($p=0.04$) significantly affected by compost application. The strongest response in 2013 occurred for petiole P with the two highest application rates significantly increasing petiole P content over the control (Table 4). Nitrogen response in 2013 was more muted, with only the 33.6 t/ha treatment showing significantly ($p<0.05$) higher petiole N than the control. Treatments were not significantly different ($p>0.05$) for petiole K in 2013.

Soil characteristics. Nearly every measured soil parameter was affected by compost application (Table 5). Both C and N significantly increased in the 22.4 and 33.6 t/ha treatments compared to the

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control in 2012 (Table 5). In 2013, the compost effect on soil C became more pronounced, with the two highest treatments significantly different from both the control and 11.2 t/ha treatments, while soil N only remained elevated at the highest application rate in 2013 (Table 5). Soil exchangeable cations were also significantly affected by compost application, with the 22.4 and 33.6 t/ha treatments higher than the control for K^+, Ca^{2+} and Mg^{2+} in 2012 (Table 5). Effects were stronger in 2013, with compost application significantly increasing soil exchangeable K^+ in the two highest treatments compared to control (Table 5). Both exchangeable Ca^{2+} and Mg^{2+} were significantly higher in the two highest treatments, compared to the 11.2 t/ha rate and control in 2013 (Table 5). Sodium was unaffected by compost application in both years.

Soil chemical properties increased systematically with increasing compost addition in both years (Table 5). Soil pH increased with compost addition, with all treatments significantly different from each other by 2013 (Table 5). Compost application increased P availability and reduced P sorption (Figure 2). In 2012, the highest application rate significantly increased Olsen extractable P compared to the control (Figure 2A). However, by 2013, Olsen extractable P was more than 4 times greater in the 33.6 t/ha treatment compared to control and was significantly higher in the 22.4 and 33.6 t/ha treatments compared to the 11.2 t/ha treatment and control (Figure 2C). Phosphorus sorption was significantly reduced from compost application in both years, with the two highest rates significantly lowering P sorption compared to the control in 2012. The treatment effect appeared muted in 2013, with P sorption only significantly reduced at the highest treatment rate compared to the control and 11.2 t/ha treatment (Figure 2B, Figure 2D). Overall, C, N, K^+, Mg^{2+}, Ca^{2+}, CEC, pH, Olsen P and P sorption all showed strong treatment effects in the first year of the study; these effects carried over to the second year and in some cases were magnified. These data support broad soil quality enhancement and increased nutrient availability following compost application to these degraded vineyard soils.

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Discussion

Vine performance. Compost application resulted in an immediate increase in pruning weight and berry weight in year one, and a significant increase in yield, pruning weight and berry weight in year two. Several studies have noted improved vine growth and yield following compost application (Pinamonti 1998, Rubio et al. 2013, Gaiotti et al. 2017, Ramos 2017). In contrast, a long-term (28 years) study of compost application in vineyard soils noted no significant beneficial effects to yield, pruning weight or berry weight from continual application of compost (Morlat 2008, Morlat and Symoneaux 2008). We posit that these differences among studies are likely due to differences in initial soil conditions. The lack of a response to compost suggests that edaphic conditions were sufficiently favorable prior to treatment, or in control plots, to sustain vigorous vine growth and yield. Here, initial soil quality was generally poor, and improvements to soil fertility from compost application removed some nutrient limitations and improved soil organic matter. Gaiotti et al. (2017) found increases in vegetative growth and a decrease in the Ravaz index from application of composted steer manure, leading to a decline in TSS and anthocyanins in juice. In contrast, we report that vegetative growth did not increase disproportionately to yield, as pruning weight and yield increased concurrently, and compost addition did not alter TSS. We ascribe these results to the multiple benefits of compost to edaphic conditions that removed both yield and vegetative growth restrictions from the relatively degraded initial soil conditions.

Compost application improved soil N and vine N status, and this led to improved yield and pruning weight. Soil N status is considered a key driver of vegetative growth and yield generation in wine grapes (Keller 2005) and compost application has been demonstrated to improve soil N status in vineyards (Korboulewsky et al. 2002, Morlat and Chaussod 2008, Bustamante et al. 2011). Mineral N fertilizer application generally increases vine N status and subsequent vine yield (Bell and Robson 1999), and compost application improves N status and yield in other crops (Eghball and Power 1999, Evanylo et

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al. 2008). Therefore, we infer that compost application improved soil and vine N status, leading to increases in yield and vegetative growth.

Vine nutrient status. Yield reduction in Pinot Noir is suggested to occur when bloom petiole N supply falls below 0.7 - 0.8% (Schreiner et al. 2018). Although petiole concentrations vary greatly by cultivar and location the 0.7 - 0.8% N range provides a benchmark to identify potential yield improvements from improved N status. In both years, mean bloom petiole N was below 0.7% in control vines and improved N nutrition led to significantly higher N status (0.73-0.77%) in vines treated with the two highest compost application rates. This suggests that control vines were N deficient with compost application improving vine N status that in turn led to improved yield and pruning weight. In contrast, we initially expected phosphorus nutrition to be a notable issue in these often high P fixing soils of volcanic origin (Cook et al. 1983). However, P levels (0.39-0.76%) were well above the 0.04% petiole P content observed by Cook et al. (1983) that led to extreme yield reductions and the 0.15% petiole P noted by Schreiner and Osborne (2018). Furthermore, soil available P in control plots (40-70 mg kg^{-1} Olsen-P) was sufficient to support a high vine yield. Therefore, P nutrition was unlikely to be a primary driver of yield and growth increases resulting from compost addition. Previous research demonstrated no effect from reduced K supply on yield or shoot growth in Pinot Noir (Schreiner et al. 2013). In previous investigations where vine K status resulted in reduced yield and vegetation growth, petiole K values were below 1% (Conradie and Saayman, 1989). Therefore, the greater than 2% petiole K values in this study were likely sufficient to support the current crop.

Soil properties. All measured soil properties were improved by compost application in the first year, and this treatment effect was generally maintained in the second year. Soil organic carbon and soil N increased from compost application, as widely observed in several other studies (Pinamonti 1998, Morlat and Chaussod 2008, Bustamante et al. 2011). It is unclear if soil C increases were due to direct

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inputs of fine organic matter in compost or increases in the stable soil C pool. Understanding the effect of compost additions on vineyard soil C stocks is an ongoing area of research (Lazcano et al. 2020). Increasing SOC has secondary beneficial effects in vineyard soils, such as decreased bulk density, improved infiltration, water holding capacity and aggregate stability, increased microbial diversity and activity, as well as potential soil carbon sequestration (Morlat and Chaussod 2008, Bustamante et al. 2011, Ramos 2017). In the current two-year study, compost application improved the C status of the soil and potentially had similar restorative effects on soil physical conditions. Vineyard soil N also routinely increases with compost application (Pinamonti 1998, Morlat and Chaussod 2008, Bustamante et al. 2011, Mugnai et al. 2012, Rubio et al. 2013). Eghball and Power (1999) suggested that about 15% of the total N becomes available in the first year following application of compost. Therefore, from the highest application of compost N in our study, around 218 g N per vine, we could expect ~33 g N per vine (equivalent to ~89 kg N/ha) available in the first year. Bell and Robson (1999) observed no negative effects from applications of up to 400 g N per vine, with optimal nutrition concluded to be between 50 and 100 g N per vine.

Phosphorus can be bound tightly to soil Fe/Al-oxides and amorphous clays in a process called “P sorption”. Phosphorus that is readily exchanged with the soil solution, and is available for plant uptake, is often called “available P”. Compost application increased P availability and reduced P sorption. Increased P availability and declines in P sorption are widely observed in vineyard soils receiving compost (Korboulewsky et al. 2002, Bustamante et al. 2011, Calleja-Cervantes et al. 2015, Wilson et al. 2016). Given the volcanic origin and highly weathered nature of these soils, our initial assumption was that P deficiency would be a significant issue in these vineyards (Cook et al. 1983). However, Olsen P values in control plots (77 mg/kg Olsen P in first year) were more than sufficient to prevent P deficiency. Nonetheless, compost application improved P availability and reduced sorption due to the added P (>81 g

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P per vine added at the highest application rate), and to the competitive inhibition of P sorption from compost decomposition products, such as organic acid anions. High levels of Olsen P (mean values >165 mg/kg Olsen P in first year) from the highest application rates could result in potential P losses to the environment. Excessive application of compost can result in large buildups of soil P in vineyards (Korboulewsky et al. 2002, Morlat 2008, Morlat and Chaussod 2008). Knowledge of soil antecedent P status should be considered in selecting the amount and type of compost applied.

Soil pH significantly increased due to compost addition, with pH increasing from 5.7 in the control to 6.7 at the highest application rate in the first year and becoming even more significant in the second year. Our previous study, at a different site, showed increases in soil pH from compost addition in a highly weathered volcanic vineyard soil (Wilson et al. 2016). Other investigations of compost addition to vineyard soils were uniformly conducted in calcareous soils and resulted in declines of soil pH (Bustamante et al. 2011, Rubio et al. 2013). In acidic soils, pH is modulated by low base saturation and high Al^{3+} saturation. Composted steer manure addition increases base saturation through addition of some $CaCO_3$ in composts and buffers Al^{3+} generated acidity through complexation/chelation.

Application of compost increased CEC and exchangeable cations with increasing compost application rates. Soil organic matter has high CEC contributing to the increased CEC values reported in other studies of compost addition to vineyard soils (Morlat and Chaussod 2008). Exchangeable Ca^{2+} and Mg^{2+} increased with compost application. Morlat and Chaussod (2008) showed increases in Mg^{2+} content from high rates of compost application. Few previous studies of compost addition to vineyard soils reported exchangeable Ca^{2+}, likely due to those studies occurring in calcareous soils (Pinamonti 1998, Morlat and Chaussod 2008, Bustamante et al. 2011). Compost application also increased exchangeable K^+ as observed in other investigations (Pinamonti 1998, Morlat and Chaussod 2008, Bustamante et al. 2011). Soil K supply was well within recommended levels (Conradie and Saayman 1989) and control vines were

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not deficient in K. However, excess K uptake can have negative effects on juice pH (Mpelasoka et al. 2003) and should be considered in compost and fertilization management.

Compost application had no effect on juice chemistry (TSS, TA, pH) in the two-year period of this study. Morlat and Symoneaux (2008) reported a change in TA in the first year, and significant changes to pH in the years following long-term compost application. They attributed the changes in juice and must pH to excess N availability from organic amendments. Compost applications reduced TSS in the study by Gaiotti et al. (2017). Reduced juice TSS from fertilization has been attributed to photosynthetic carbon source-sink relationships between shoots and berries, with excess vigor from fertilization reducing sugar accumulation in berries (Keller 2005). However, no changes to vine balance or juice chemistry (e.g., TA, pH and TSS) were observed among treatments in this study.

Compost application rates. An important finding of this research was the effect of compost application rate on yield, vine nutrients, soil fertility and soil chemical properties. Previous studies in vineyard soils did not investigate compost application rates explicitly. Here, the lowest application rate had no significant effect on yield, pruning weight, berry weight or petiole nutrients in either year of the study. Similarly, there were no differences between control and low application rate treatments for soil CEC, total N, SOC, or exchangeable base cations in either year. Soil pH was the only soil property significantly different between control plots and low application rate soils. Conversely, differences were detected in soil properties and berry weight for the higher application rates (22.4 & 33.6 t/ha). The 22.4 and 33.6 t/ha application rates tended to have higher yield, berry weight and pruning weight, while the lowest application rate was not different from the control. For the duration of this study, these data infer a threshold effect for compost on these degraded vineyard soils, and that for a single dose, more was better, at least up to 33.6 t/ha. Similar to the current study, Evanylo et al. (2008) found that low compost application rates did not increase yield in corn, while higher doses had significant effects. Therefore, we suggest that single, large doses of compost to degraded vineyard soils can have at least two years of positive effects on vine parameters and soil properties without adverse effects on vine balance or juice characteristics. In contrast, a single application at low rates may have little or no detectable effects. Overall, improved soil fertility and soil chemical characteristics following compost application led to improved vine health and performance in these degraded soil sites.

Conclusions

A single 22.4 or 33.6 t/ha dose of compost to degraded vineyard soils resulted in a two-year improvement to vine performance, soil fertility and soil chemical characteristics. Importantly, these improvements in vine performance did not adversely affect vine balance or juice characteristics. Meanwhile, a smaller compost application rate (11.2 t/ha) had no significant effects on soil fertility, soil chemical characteristics or vine performance. Given the many benefits of compost application to soil quality (physical, chemical, and biological soil quality), it is unclear which of the improved soil properties was most important to improved vine performance. However, given low petiole N values in control vines, it is likely that some yield and growth limitations due to N deficiency were ameliorated by compost application. The positive effects reported here from higher rates of compost may be preferentially exhibited by degraded and eroded soils, and/or volcanic and highly weathered vineyard soil systems with underperforming vines, and depend on antecedent soil conditions and compost characteristics (e.g. C:N ratios). We conclude that intermediate to higher application rates of compost (22.4 to 33.6 t/ha) provide at least a two-year beneficial effect to soil fertility and vine performance in degraded vineyard soils in California, without compromising vine balance or juice quality.

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2020.20012
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Table 1 Characterization of Applied Compost - Total Elemental Analysis[1]

Ash	C	N	P	K	Na	Ca	Mg	Fe	Cu	Mn	Zn	S	Cl
------------------------------g/kg-------------------------								--------------------mg/kg------------------					
589	228	18.2	6.8	25.6	7.9	32.6	10	9455	55.9	377	181	0.87	1.4

[1] Reported on a total elemental basis

Table 2 Compost application rates applied in study in tons per hectare and kg per vine. Grams of total nitrogen, phosphorus and potassium applied via compost in grams per vine.

Application Rates				
Compost		N	P	K
t/ha	kg/vine	------------------------g/vine----------------------		
11.2	4.2	72.5	27.2	104.3
22.4	8.4	145	54.4	204.1
33.6	12.5	217.7	81.6	308.4

Table 3 Effect of compost application rate (0, 11.2, 22.4 and 33.6 t/ha) on harvest juice titratable acidity (TA), total soluble solids (TSS), and pH. Compost application rate (0, 11.2, 22.4 and 33.6 t/ha) effect on the Ravaz index (per vine yield divided by per vine pruning weight). Results of ANOVA analysis showed no significant differences with respect to juice characteristics or vine balance in each year (*p* > 0.05). Values in parentheses are standard errors of the mean.

Year	Rate	TA	TSS	pH	Ravaz Index
	t/ha	g tartaric/100 mL	°Brix		ratio
2012	0	0.41 (0.01)	25.0 (0.39)	3.68 (0.06)	3.87 (0.19)
	11.2	0.43 (0.03)	24.6 (0.47)	3.63 (0.07)	3.64 (0.68)
	22.4	0.43 (0.02)	25.7 (0.61)	3.48 (0.05)	3.90 (0.35)
	33.6	0.44 (0.01)	26.3 (1.00)	3.60 (0.02)	3.61 (0.32)
2013	0	0.66 (0.05)	23.8 (0.95)	3.50 (0.08)	3.58 (0.55)
	11.2	0.69 (0.07)	24.2 (0.64)	3.58 (0.09)	3.37 (0.80)
	22.4	0.64 (0.02)	23.9 (0.6)	3.49 (0.07)	3.79 (0.62)
	33.6	0.66 (0.05)	24.3 (0.89)	3.56 (0.09)	3.28 (0.29)

Table 4 Effect of compost application rate (0, 11.2, 22.4 and 33.6 t/ha) on vine petiole N, P and K concentrations sampled at bloom in 2012 and 2013. Within each year, means with different letters indicate significant differences by Tukey's honest significant difference (HSD) at $p < 0.05$. Values in parentheses are standard deviations.

Year	Rate	N	P	K
	t/ha	------------------% petiole--------------------		
2012	0	0.69^{c} (0.02)	0.39^{c} (0.12)	2.80^{c} (0.41)
	11.2	0.72^{bc} (0.02)	0.47^{bc} (0.09)	3.3^{bc} (0.46)
	22.4	0.76^{ab} (0.02)	0.51^{b} (0.10)	3.7^{ab} (0.58)
	33.6	0.77^{a} (0.03)	0.67^{a} (0.05)	4.1^{a} (0.72)
2013	0	0.69^{c} (0.02)	0.39^{c} (0.12)	2.80^{c} (0.41)
	11.2	0.70^{b} (0.04)	0.66^{ab} (0.16)	2.85^{a} (0.65)
	22.4	0.73^{ab} (0.04)	0.72^{a} (0.19)	3.43^{a} (0.28)
	33.6	0.75^{a} (0.02)	0.76^{a} (0.17)	3.51^{a} (0.29)

Table 5 Effect of compost application rate (0, 11.2, 22.4 and 33.6 t/ha) on soil exchangeable cations, total carbon and nitrogen concentrations, cation exchange capacity and soil pH. Within each year, means with different letters indicate significant differences by Tukey's honest significant difference (HSD) at $p < 0.05$. Values in parentheses are standard deviations.

Year	Rate	Ex-K	Ex-Ca	Ex-Mg	Ex-Na	C	N	CEC	pH
	t/ha	-------------------------mg/kg---------------------				------------%-------------		cmol/kg	(1:1$_{\text{water}}$)
2012	0	321^{b} (91)	829^{b} (188)	327^{b} (44)	35^{a} (5.5)	1.10^{c} (0.16)	0.04^{c} (0.01)	9.8^{b} (1.9)	5.8^{c} (0.21)
	11.2	436^{ab} (150)	934^{b} (248)	352^{b} (51)	32^{a} (6.0)	1.57^{bc} (0.55)	0.09^{bc} (0.03)	10.0^{ab} (1.7)	6.2^{b} (0.26)
	22.4	529^{ab} (45)	1169^{ab} (291)	380^{b} (65)	26^{a} (6.1)	2.43^{b} (0.81)	0.16^{b} (0.07)	11.5^{ab} (1.5)	6.4^{b} (0.21)
	33.6	600^{a} (131)	1500^{a} (233)	476^{a} (84)	30^{a} (8.1)	3.60^{a} (0.64)	0.27^{a} (0.07)	13.5^{a} (1.3)	6.8^{a} (0.25)
2013	0	364^{c} (46)	637^{b} (101)	262^{b} (30)	25^{a} (8.6)	0.86^{c} (0.24)	0.06^{b} (0.02)	8.0^{c} (0.8)	5.8^{d} (0.13)
	11.2	400^{bc} (21)	1010^{b} (208)	353^{b} (24)	27^{a} (3.7)	1.98^{bc} (0.69)	0.14^{b} (0.04)	10.5^{bc} (1.3)	6.2^{c} (0.17)
	22.4	634^{ab} (113)	1425^{a} (215)	486^{a} (64)	26^{a} (5.9)	3.74^{b} (0.91)	0.32^{b} (0.07)	13.3^{ab} (1.6)	6.8^{b} (0.13)
	33.6	762^{a} (185)	1646^{a} (197)	605^{a} (75)	28^{a} (5.6)	6.59^{a} (2.22)	0.60^{a} (0.23)	15.2^{a} (1.9)	7.2^{a} (0.06)

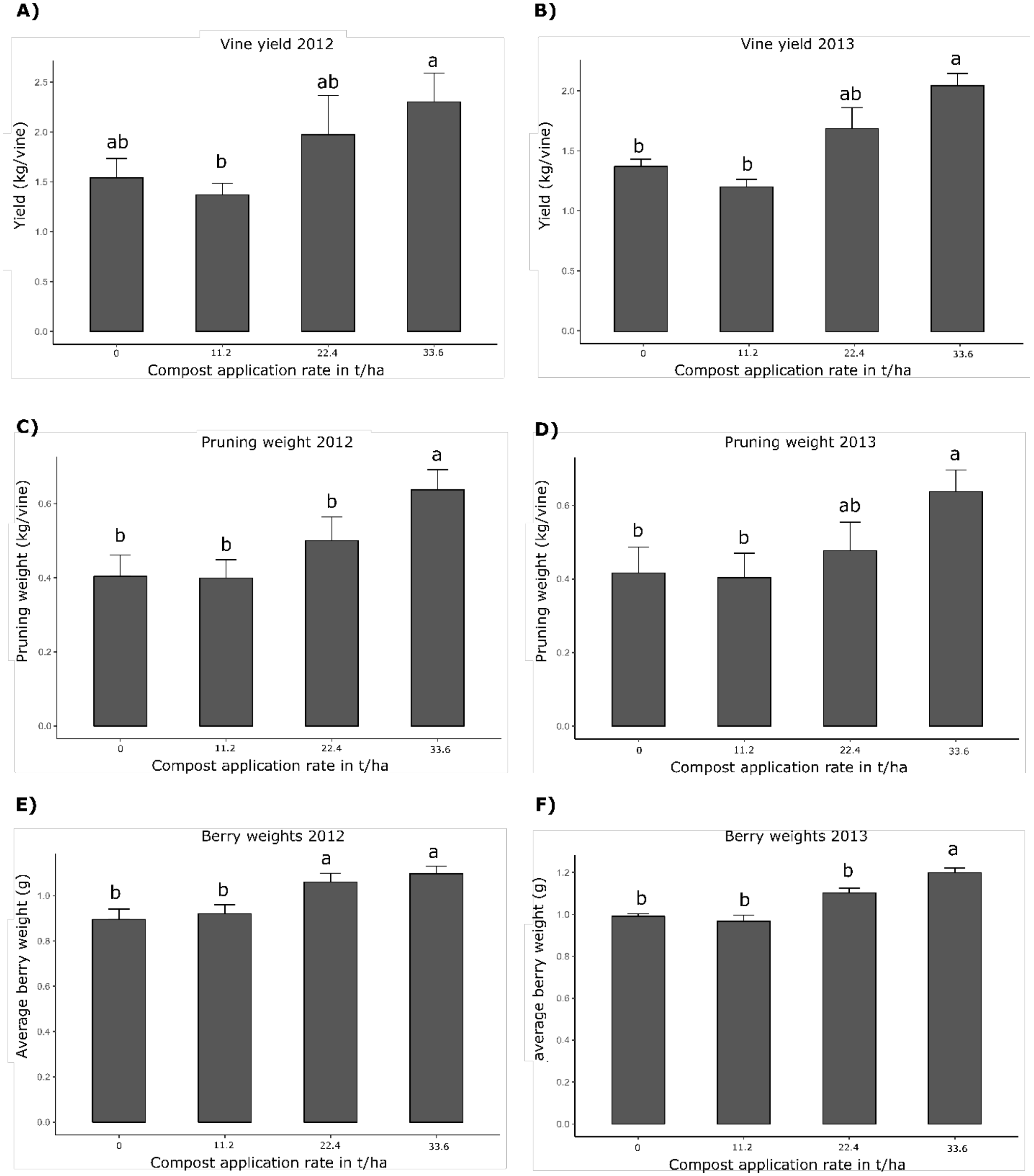

Figure 1 Effect of compost application rate (0, 11.2, 22.4 and 33.6 t/ha) on vine yield in 2012 (**A**) and 2013 (**B**); pruning weight in 2012 (**C**) and 2013(**D**); and berry weight in 2012 (**E**) and 2013 (**F**). Error bars represent standard error of the mean. Within a single graph, means with different letters indicate significant differences by Tukey's honest significant difference (HSD) at *p* < 0.05.

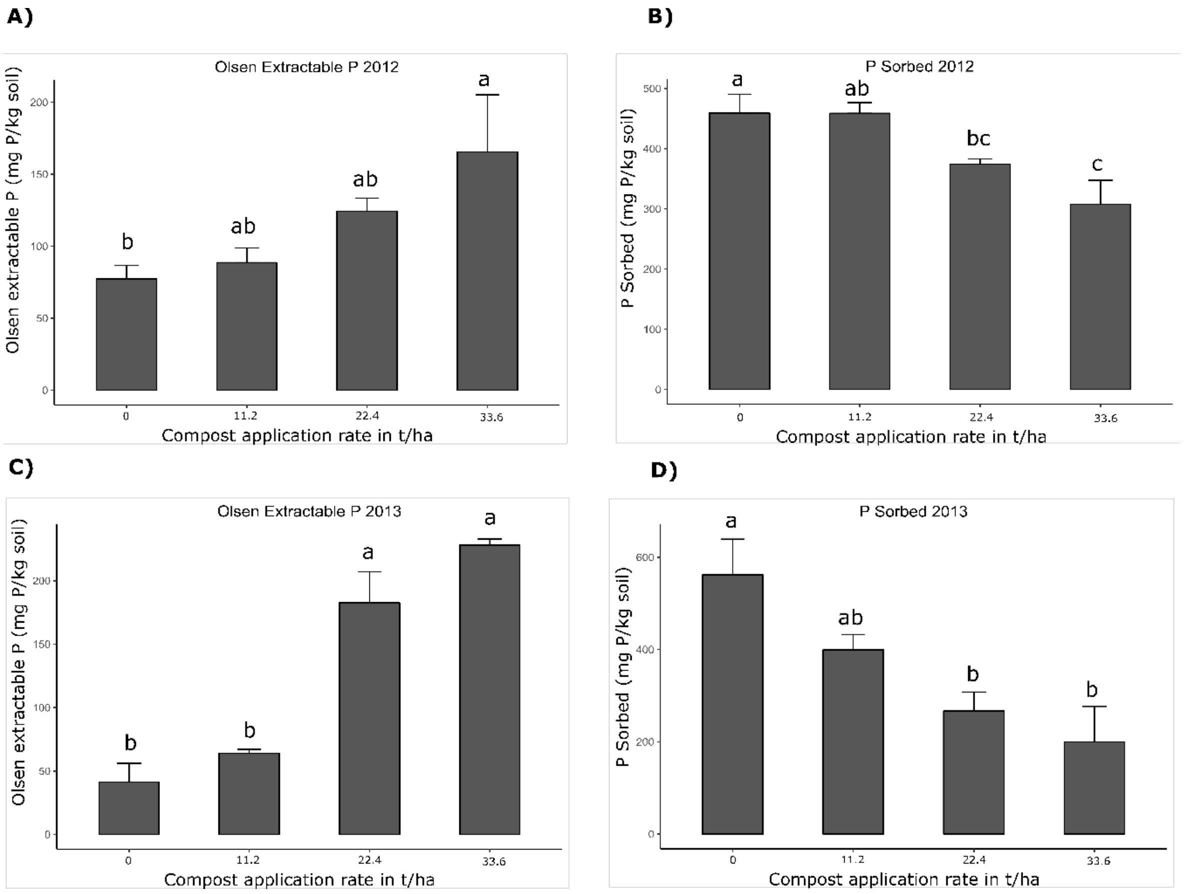

Figure 2 Effect of Compost application rate (0, 11.2, 22.4 and 33.6 t/ha) on Olsen extractable P in 2012 (**A**) and 2013 (**C**) and P sorption in 2012 (**B**) and 2013 (**D**). Within a single graph, means with different letters indicate significant differences by Tukey's honest significant difference (HSD) at $p < 0.05$.

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Supplemental Table 1

Results of polynomial orthogonal contrasts investigating the compost rate response in per vine yield, per vine pruning weight and berry weight.

Year	Rate Response	Yield	Pruning Weight	Berry Weight
			p<F	
2012	Linear	0.033*	0.008**	<0.001***
	Quadratic	0.371	0.235	0.882
	Cubic	0.398	0.787	0.241
2013	Linear	<0.001***	0.034*	<0.001***
	Quadratic	0.035*	0.230	0.022*
	Cubic	0.136	0.998	0.076

*Indicates significance at $p < 0.05$. ** Indicates significance at $p < 0.01$. *** Indicates significance at $p < 0.001$.